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Review

Electronic textiles for energy, sensing, and communication

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SUMMARY

Electronic textiles (e-textiles) are fabrics that can perform electronic functions such as sensing, computation, display, and communication. They can enhance the functionality of clothing in a variety of convenient and unobtrusive ways, thus have garnered significant research and commercial interest in applications ranging from fashion to healthcare. Recent advances in materials science and electronics have given rise to variety of e-textile components, including sensors, energy harvesters, batteries, and antennas on flexible and breathable textiles substrates. In this review, we discuss recent advances in the development of e-textiles for energy, sensing, and communication. In addition, we investigate challenges in the integration of components to realize e-textile systems, and highlight opportunities enabled by innovations in materials science, engineering, and data science.

INTRODUCTION

Wearable technologies allow digital tools to be conveniently and unobtrusively integrated into our everyday lives. Electronic textiles (e-textiles) represent an important example that takes advantage of clothing as a platform for sensing, actuation, display, communication, energy harvesting, energy storage, and computation. Whereas earlier e-textile were designed based on simply attaching conventional electronic components attached onto clothing, recent advances in material science and electronics have enabled e-textiles that are able to perform a wide variety of electronic functionalities while being flexible and breathable. Such e-textiles have gained significant attention both in the industry and academia and have been demonstrated for a broad range of applications, including Internet of things (IoT), artificial intelligence (AI) (Matijevich et al., 2020), body motion tracking (Chun et al., 2018; Kim et al., 2019b), gaming(Zhou et al., 2018), pressure mapping (Lim et al., 2020), rehabilitation, healthcare (Fan et al., 2020; Li et al., 2018a; Teferra et al., 2019), smart wearables (Carneiro et al., 2020; Fernández-Caramés and Fraga-Lamas, 2018; Gong et al., 2019), and smart garments (Castano and Flatau, 2014; Ou et al., 2019; Yin et al., 2018b).

E-textile-related technologies have been drawing great attention from researchers and most of the review articles on e-textiles are from the point of view of materials or methods of fabrication (Wang et al., 2021; Yong Zhang et al., 2021; Zhang et al., 2021). In this article, we present the key components needed to build independent e-textile systems and review recent progress in the development of e-textiles by their functionality: sensing, communication, and energy harvesting and storage, with emphasis on limitations and opportunities for their integration into functional systems. E-textile systems require several key components to perform basic functions with sufficient level of autonomy, including sensors for data acquisition, energy sources for system power supply and regulation, communication modules for data transmission and interfacing, and reliable interconnections that connect different modules into an integrated system. Figure 1 shows a person wearing a smart running suit that is equipped with various textile-based components. Here, the blue arrows indicate the transmission of data captured by different textile-based sensing elements. Specifically, the physical and bio/chemical data are transmitted from the sensors via conducting elements (e.g., conductive threads) to a wireless communication hub, that then send data wirelessly to a computing unit for further analysis. The red arrows indicate how the independent smart suit is powered, using either energy harvesters or energy storage devices. These components (sensor, energy harvester/storage, and communication devices as well as connection) assembly into an independent smart e-textile system, and is discussed in detail in the following sections.

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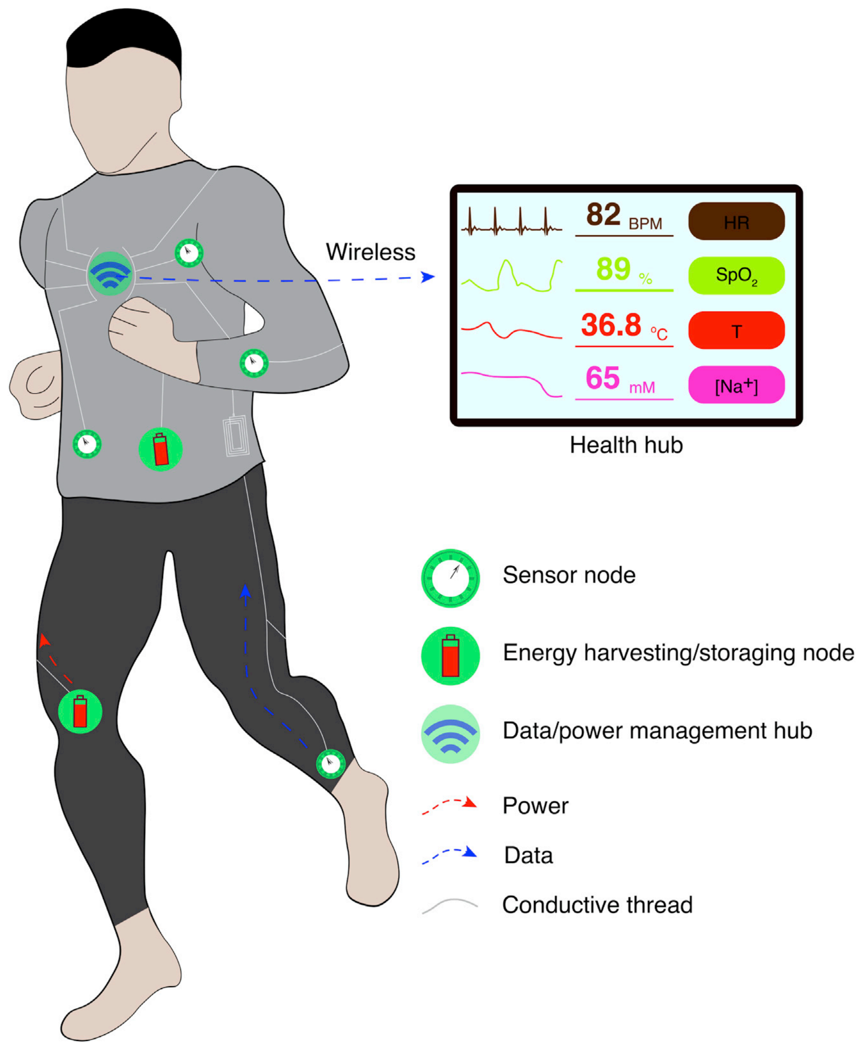

Figure 1. Smart e-textile system: energy, sensing, and communications
Illustration of an independent smart e-textile system with capabilities of sensing, energy harvesting, and communication. The sensing data are wirelessly uploaded to cloud.

SENSORS FOR E-TEXTILE SYSTEM

E-textiles can interface with large areas of the human body to capture important information about the physiological state and the environment. In this section, we will discuss various textile-based sensors that have been developed to measure physical and bio/chemical parameters.

Physical sensors

E-textiles can measure changes in the physical properties of the underlying textiles. Because they consist of woven networks of flexible fibers, textiles can easily be mechanically deformed. Furthermore, e-textiles are mainly used in smart wearables which require motion tracking of human body's physical or mechanical movements (Roudjane et al., 2020). Thus, there are a vast number of reports on e-textiles with strain or pressure sensing capability (Islam et al., 2020; Seyedin et al., 2019).

One approach to produce textile-based sensors is to use fibers that are intrinsically conductive. As an example, highly stretchable and washable piezoresistive microfiber strain sensors were developed that can withstand 120% strain with electrical conductivity of 3.27 $\pm$ 0.08 MS/m (Yu et al., 2018). Such microfiber sensor was fabricated by encapsulating liquid metal eutectic Ga-In alloy (eGaIn) inside a tiny elastomeric microtube made of polydimethylsiloxane (PDMS) with diameter of 160 μm. Owing to the small size of the sensor, it can be weaved into fabrics and even a glove as shown in Figure 2A(Yu et al., 2018). By stretching the textile, the sensor inside the fabric is elongated, thus deforming the PDMS hollow tube and displacing the liquid metal inside, which resulted in an increase of electric resistance of the sensor. In another example, a dual-core capacitive microfiber sensor was fabricated (Yu et al., 2019). This microfiber sensor is comprised of a dual-lumen elastomeric microtube filled with liquid metallic alloy, which enables continual strain perception even after being completely severed. As shown in Figure 2B (Yu et al., 2019, p.), the microfiber sensors were sewn into a fabric glove, enabling the glove to capture the gesture of the hand and monitor respiration rate based on capacitive change of $\Delta C/C_0$.

Rather than using intrinsically conductive fibers, a number of studies focused on coating conventional textile fibers with conductive materials. For example, a wearable silk fabric based on carbonizing the pristine silk fiber was reported for stretchable strain sensing (Wang et al., 2016). The sensor showed a maximum strain of 520% and withstood 6,000 tensile cycles at 100% strain. Similar carbonization method was used in other studies on e-textiles. These include piezoresistive-type MoS_2-coated carbonized silk fabric pressure sensor (Lu et al., 2020), polyaniline and carbon nanotubes-coated Au/nylon fiber (Zhao et al., 2020a), conductive graphene-based E-textile via bubble-exfoliation method and dip coating (Hu et al., 2020b). This popular dip coating method was used to produce resistive e-textiles by simply coating a conductive layer onto the surface of a fabric (Bi et al., 2018; Cai et al., 2017; Li et al., 2019; Lian et al., 2020; Yang et al., 2018a; Yang et al., 2020; Yang et al., 2018b). Another "all textile-based" strain sensor used an elastic fabric as a substrate with conductive yarn as the resistive sensing component weaved into the substrate in different patterns (Park et al., 2019). The sensor is reported to be able to detect bending and rotation of human joints. Other than resistive and capacitive textile-based sensors, triboelectric nanogenerators technologies can also be used for pressure sensing e-textiles. A machine-washable and breathable pressure sensor based on triboelectric nanogenerators was introduced (Zhao et al., 2020b). Two types of yarns were designed: Cu-coated polyacrylonitrile (denoted as Cu-PAN) yarns and parylene-coated Cu-PAN (denoted as parylene-Cu-PAN) yarns. When the Cu-PAN yarns and parylene-Cu-PAN yarns are in contact with each other in a fabric, a voltage signal is produced when there is a contact area change due to applied external pressure. The study also showed that the yarns can be knitted into a piece of pressure sensing fabric glove using a knitting machine as shown in Figure 2C (Zhao et al., 2020b).

Apart from mechanical force/pressure-detectable e-textile sensors, e-textiles have also been developed to sense other physical parameters in the environment. For example, environmental humidity was reported to be detectable with a flexible humidity capacitive sensing system, in which the sensor part is composed of two copper wires with a layer of yarns in between as the dielectric layer, as illustrated in Figure 2D (Ma et al., 2019). As the yarns absorb the moisture in the atmosphere, the permittivity of the dielectric increases, leading to increase in capacitance of the textile sensor. The moisture sensing capability of e-textile can be further extended to moisture management. A double-sided synergetic Janus textile was developed for moisture/thermal management, as demonstrated in Figure 2E (Wang et al., 2020b), with one side of the textile coated with hydrophilic polymer and the other side coated with hydrophobic polymer. The difference of moisture absorption resulted in difference in textile porous size, leading to thermal managing capability. Without having any coating on the fabric, another moisture-sensing e-textile was fabricated by simply twisting the silk yarns, turning the silk into an artificial torsional silk muscle (Jia et al., 2019). This sensor provided a reversible torsional stroke of $547^\circ\ mm^{-1}$ when exposed to water fog and the coiled-and-thermoset silk yarns provide a 70% contraction when the relative humidity was changed from 20% to 80%.

E-textile can also be designed to enable multiple sensing capabilities. A silk composite electronic textile combo sensor was designed for measuring both temperature and pressure (Wu et al., 2019). As shown in Figure 2F (Wu et al., 2019), the fiber sensor is composed of an external Ecoflex sealing layer, silk fibers encapsulated with CNTs and $[EMIM]Tf_2N$ as the thermal conductive middle layer, and with polyester fibers as the supporting core. Temperature change detected by the resistance of the silk fiber middle layer achieved a sensitivity of $1.23\%\ ^\circ C^{-1}$, while the pressure sensed by the capacitance in between two contacted sensor fibers achieved sensitivity of $0.136\ kPa^{-1}$. By using chemical vapor deposition (CVD) method to deposit a trilayer graphene (TLG) on top of polypropylene (PP) textile, a carbon−graphene temperature sensing e-textile was reported to operate at voltage as low as 1.0 V(Rajan et al., 2020).

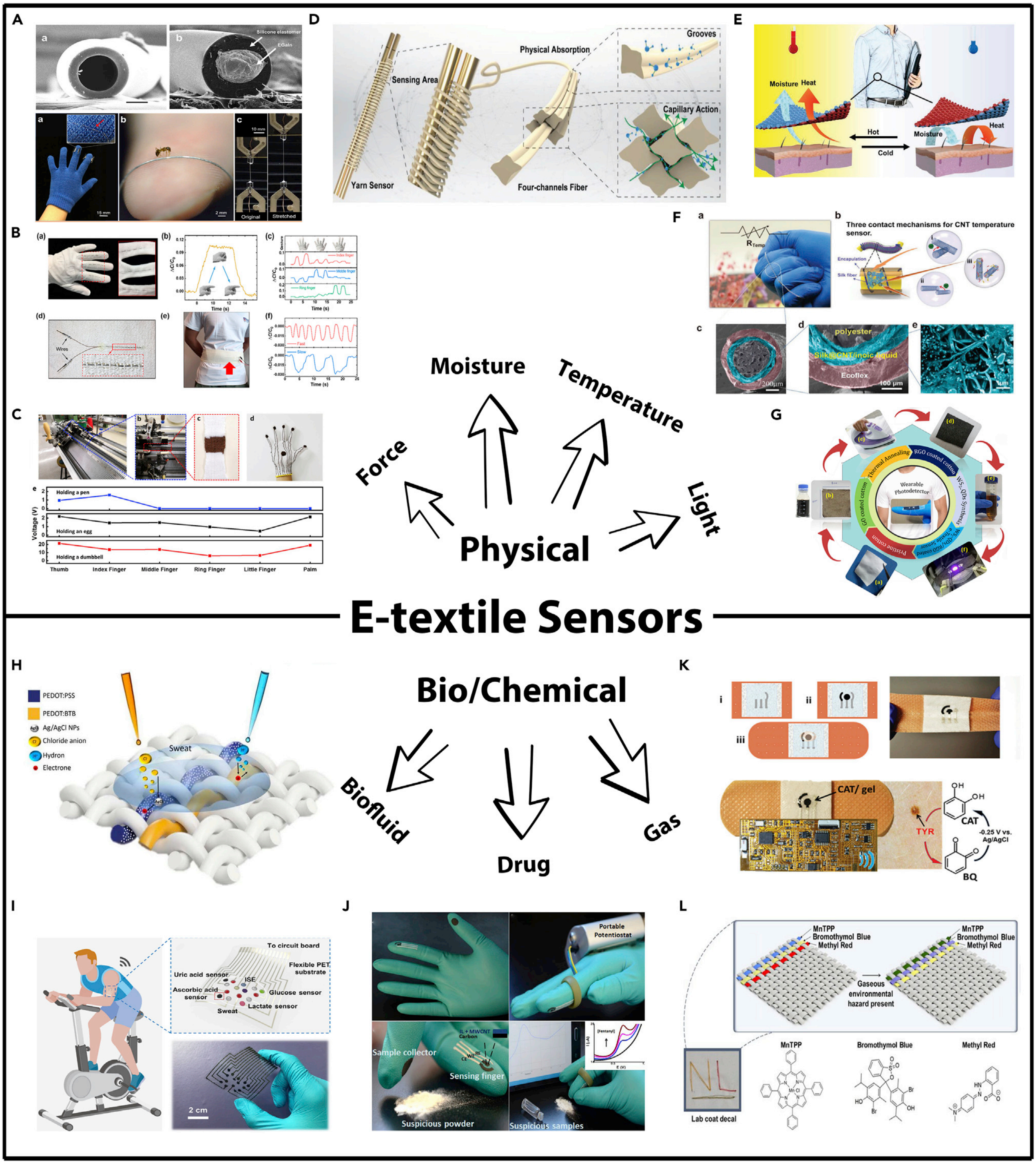

Figure 2. E-textile sensors

(A–L) Force sensing: (A) highly stretchable and wearable piezoresistive microfiber liquid-metal based sensor (Yu et al., 2018), (B) dual-core capacitive microfiber sensor for e-textile application (Yu et al., 2019, p.), and (C) machine-knittable smart glove for pressure sensing (Zhao et al., 2020b). Moisture sensing: (D) yarn-type humidity sensor (Ma et al., 2019), and (E) smart Janus textile moisture/thermal management (Wang et al., 2020b). Temperature sensing: (F) silk composite e-textile temperature sensor (Wu et al., 2019). Light sensing: (G) WS_2 quantum dots on e-textile as a wearable UV photodetector (Abid et al., 2020). Biofluid sensing: (H) biosensing textile platform for chloride ion and pH sensing (Possanzini et al., 2020), and (I) integrated e-textile sensor patch for real-time and multiplex sweat analysis (He et al., 2019). Drug sensing: (J) glove-based sensor for fentanyl detection (Barfidokht et al., 2019). Chemical sensing: (K) enzyme skin-cancer biomarker sensor (Manjakkal et al., 2019). Gas sensing: (L) Colorimetric gas sensing threads for e-textile (Owyeung et al., 2019).

Other than sensing temperature and humidity, e-textile can detect wavelength of light beam. A novel photodetecting sensor was produced based on a WS_2 quantum dots and reduced graphene oxide (RGO) (WS_2-QDs/RGO) heterostructure (Abid et al., 2020). By coating the RGO and WS_2 on a piece of pure cotton textile, as shown in Figure 2G (Abid et al., 2020), they were able to place the smart fabric on the back of a finger for photodetection of a 405 nm illumination source and the photoresponsivity can reach up to 5.22 mA W^{-1} at 1.4 mW mm^{-2} power density.

Chemical/biochemical sensors

In addition to the great effort in developing textile-based physical sensors, many chemical/bio/electrochemical sensors were being developed for the sensing of chemical biomarkers and external environmental markers that are closely associated with our daily lives. Considering the fact that most of the e-textiles are in close contact with the human skin, textile-based sensors entail intimate contact that endows easy access to various biofluids.

Shown in Figure 2H, a textile-based biofluidic sensor is produced from simple threads. After being coated with the conducting polymer poly(3,4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS), the thread is functionalized with nanocomposite and chemical-sensitive dye to detect chloride ion and pH level in sweat (Possanzini et al., 2020). Another flexible sweat analysis patch sensor was designed based on a silk-fabric-derived carbon textile for simultaneous detection of six health-related biomarkers in sweat—glucose, lactate, ascorbic acid, uric acid, Na^+, and K (He et al., 2019). As demonstrated in Figure 2I, the intrinsically nitrogen (N)-doped porous structured carbon textile (SilkNCT) was used (or combined with other components) as the working electrode of the electrochemical sensors (He et al., 2019). The sweat sensor patch was further integrated with signal collection and transmission components, making it possible to conduct real-time monitoring of biomarkers in sweat. Mask printing method was applied to fabricate another sweat-chemical-sensing system by printing thin layers of electrodes on the surface of a glove to measure diverse biomarkers of natural sweat, including zinc, ethanol, pH, and chloride (Bariya et al., 2020; Tang et al., 2021; Wang et al., 2018).

While smart wearable sensors can sense chemicals in our biofluids and provide critical information regarding the health status of our body, they can also be applied for detection of foreign chemicals for environmental, forensic, or military applications. For example, a wearable electrochemical glove-based sensor was reported to conduct rapid and on-site detection of fentanyl, in order to prevent drug abuse (Barfidokht et al., 2019). In this device, the flexible electrochemical sensors were integrated on the fingertips of the glove using screen printing method. The electrochemical sensor for fentanyl is based on its irreversible oxidation on the composite electrode which consists of multi-walled carbon nanotubes (MWCNT) and ionic liquid (shown in Figure 2J) (Barfidokht et al., 2019). The glove sensor can detect fentanyl in both liquid and powder forms with a detection limit of 10 μM using square-wave voltammetry. Similarly, electrochemical sensors for other chemicals based on textile have been developed for the detection of nerve agents, pollutants, or explosives (Bandodkar et al., 2013; Goud et al., 2021; Malzahn et al., 2011). Chemicals under human skin can also be detectable with a bandage-based sensor with minimally invasive microneedles for skin melanoma screening (Ciui et al., 2018). In another study, a textile-based potentiometric electrochemical pH sensor was reported with thick film graphite composite as the sensitive electrode and Ag/AgCl as the reference electrode. Both electrodes were printed on cellulose-polyester blend cloth and the sensor was able to measure pH ranging from 6.0 to 9.0 (Manjakkal et al., 2019). The wearable electrochemical sensors can even detect tyrosinase (TYR) enzyme skin-cancer biomarker with the catechol substrate. As illustrated in Figure 2K, in the presence of TYR, catechol will be oxidized into benzoquinone, which can be detected amper metrically (Manjakkal et al., 2019).

Instead of sensing chemicals in liquid or solid forms, wearable sensors can also sense chemical in its gaseous form. Shown in Figure 2L is a colorimetric gas-sensing e-textile fabricated by applying optically responsive dyes on the thread substrate, before being put into the acetic acid for cleaning and PDMS for physical entrapment of the dye (Owyeung et al., 2019). Three types of dyes were tested: 5,10,15,20-Tetraphenyl-21H,23H-porphine manganese (III) chloride (MnTPP), methyl red (MR), and bromothymol blue (BTB) for sensing two volatile gases, ammonia and hydrogen chloride. The concentration of gases was tested from 50 to 1000 ppm.

Table 1 compiles the sensor type, material used, fabrication method used, flexibility, and washability and other information of the physical textile sensors. In terms of material, most of the sensors consists of at least one flexible substrate (fabric, cotton, or yarn, etc.), providing the sensor with a physical flexible property;

Table 1. Summary of e-textile physical sensors including the sensor type, material, fabrication method, and washability

Sensor type	Material	Fabrication	Washability	Ref.
Pressure	eGaIn + PDMS + fabric	Microfiber fabrication	Yes	(Yu et al., 2018)
	MoS2 + Carbon + silk	Coating		(Lu et al., 2020)
	Graphene + Polymer + Cu particles	Printing and dyeing	Yes	(Hu et al., 2020b)
	Mxene + cotton + PI tape	Dip coating		(Li et al., 2019)
	AgNW + cotton	Dip coating	Yes	(Lian et al., 2020)
	Cu-PAN yarn + parylene-Cu-PAN yarn	Coating + weaving	Yes	(Zhao et al., 2020b)
Strain	eGaIn + PDMS + fabric	Microfiber fabrication	Yes	(Yu et al., 2019)
	Carbon + silk	Coating	Yes	(Wang et al., 2016)
	Pen ink + Cupra fabric (CF)	Dip coating	Yes	(Bi et al., 2018)
	rGO + nylon/PU fabric,	Dip coating	Yes	(Cai et al., 2017)
	CNT + cotton	Dip coating	Yes	(Yang et al., 2018a)
	Carbonic pigment ink + Polyamide fabrics	Dip coating	Yes	(Yang et al., 2020)
	rGO + textile	Dying	Yes	(Yang et al., 2018b)
	Conductive yarn + textile	Weaving		(Park et al., 2019)
Moisture	Copper wire + yarn	Wrapping		(Ma et al., 2019)
	Silk	Twisting		(Jia et al., 2019)
Moisture thermal	Hydrophilic polymer + hydrophobic polymer	Polymer Coating		(Wang et al., 2020b)
Temperature pressure	Ecoflex + silk + CNT + [EMIM]Tf2N + polyester fibers	Encapsulating		(Wu et al., 2019)
Temperature	Graphene + polypropylene textile	CVD		(Rajan et al., 2020)
Light	WS_2 quantum dots + rGO	Chemical coating		(Abid et al., 2020)

another inevitable part of these sensors is the conductive component (carbon, eGaIn, etc.), which will allow electrical signal to pass within or on the surface of the substrate. Thus, we can see that some of the sensors share similar fabrication methods, especially (strain or pressure) sensors. Dip coating is one of the most popular ways to produce for sensors, as by using this method, one can easily coat a conductive/functional layer on top a normal piece of fabric or textile. However, with different functional components, specifications such as sensitivity, range, and cycle life of different sensors can differ a lot.

Table 2 shows the compilation of different bio/chemical sensors. It can be seen that these types of sensors comparatively are more complex than physical sensors. In order to obtain the chemical sensing capability, electrodes are necessary to perform different level of chemical reaction on a flexible substrate. Thus screen printing or mask printing is very popular for being able to coat a tiny piece of electrode on the substrate.

It is noticeable that the novel 2D carbon-based materials significantly contribute to the fast development of e-textile sensors. Among these materials, Graphene, RGO, MWCNT, and Mxene are most commonly used by researchers. In e-textile sensors, 2D carbon-based materials are not only able to perform as the conducting or sensing component in a sensor but also the small size or low thickness characteristics ensuring the flexibility of the e-textile sensors.

ENERGY FOR E-TEXTILE SYSTEM

The operation of various e-textile sensing modules and the downstream data processing, transmission, and interfacing will have to rely on a compatible energy system. In a self-sustainable independent e-textile system, wearable energy harvesters scavenge energy from various sources and energy storage modules

Table 2. Summary of e-textile bio/chemical sensors including the sensor type, material, fabrication method, and washability reported in the literature

Sensor type	Material	Fabrication	Ref.
Biofluid (sweat)	PEDOT:PSS + thread	Dying	(Possanzini et al., 2020)
	nitrogen–doped porous structured carbon textile	Carbonization	(He et al., 2019)
	Au + nitrile	Mask printing	(Bariya et al., 2020)
	Ag + Ecoflex + Porous PVA Hydrogel + poly (ethylene terephthalate) (PET)	Mask printing	(Tang et al., 2021)
	MWCNT + Nitrile + Ag/AgCl	Mask printing	(Wang et al., 2018)
Chemical	MWCNT + ionic liquid	Screen printing	(Barfidokht et al., 2019)
	Spandex + SEBS + Ag/AgCl	Screen printing	(Goud et al., 2021)
	Ag/AgCl + synthetic rubber neoprene	Screen printing	(Malzahn et al., 2011)
	microneedles + carbon + bandage	Screen printing	(Ciui et al., 2018)
	graphite composite + Ag/AgCl + catechol substrate	Printing	(Manjakkal et al., 2019)
	MnTPP + MR + BTB + PDMS	Dying	(Owyeung et al., 2019)

regulate the harvested energy and enhance system reliability. In this section, we discuss the commonly employed strategies in developing various energy harvesters and storage devices, and the integration thereof. The specific requirements to meet the standards of an e-textile module and their current limitations are also summarized.

Textile-based energy harvesters

As the power source for an energy independent autonomous system, the performance of energy harvesters determines the admissible functionality of the system. To fully utilize the diverse sources of energy, energy harvesters based on different energy generation mechanisms have been developed, harvesting solar or thermal energy from the surrounding environment (Chen et al., 2016; Ding et al., 2020; Elmoughni et al., 2019; Hashemi et al., 2020; Hinckley et al., 2021; Pu et al., 2016b; Wen et al., 2016, 2020), or the bioenergy associated from the human activities and metabolism (Bandodkar, 2017; Bandodkar and Wang, 2016; Dong et al., 2019; Jeerapan et al., 2016; Lund et al., 2018; Xiong and Lee, 2019; Zhang et al., 2015b). In general, we can classify the energy harvester commonly seen in e-textile systems into two types: the ones that harvest environmental energies, namely, solar cells that harvest via photovoltaic effect and thermoelectric generators (TE) that harvest by exploiting the Seebeck effect (Bell, 2008); and the ones that harvest from the human body itself, namely, piezoelectric nanogenerators (PENG) and triboelectric generators (TENG) that harvest biomechanical energy from the movements of human body, and biofuel cells (BFC) that generate electricity using microbial or enzymatic redox reactions fueled by metabolites in human biofluids (Dong et al., 2019; Jeerapan et al., 2020; Pang et al., 2017; Ryu et al., 2019). Other types of wearable energy harvesters have also been proposed based on motion-powered electromagnetic generators (Quan et al., 2015; Zhang et al., 2015a; Zhang et al., 2019), breathing-powered pyroelectric generators (Li et al., 2020a; Thakre et al., 2019; Xue et al., 2017), or antenna-based electromagnetic radiation harvesters (Abadal et al., 2014), but are less relevant to the scope of this review and are not discussed here. In general, the fabrication of the textile-based energy harvesters can be differentiated into the yarn/wire/thread-based devices that constitute the e-textile system from a "bottom-up" approach, and the ones that are directly fabricated onto fabrics/textiles in a "top-down" approach. The material and characteristics of examples discussed below were summarized in Table 3.

The fabrication of textile-based solar cells requires extensive material and structural engineering to obtain the desired flexible and wearable form factors. Opposed to traditional silicon-based photovoltaic materials, textile-based solar cells that rely on novel organic photovoltaic (OPV), dye-sensitized, and perovskite materials can be fabricated by solution compatible processes due to their thin-film nature which enables flexibility (Hatamvand et al., 2020; Li et al., 2015; Liu et al., 2018; Qiu et al., 2016; Xu et al., 2020). As shown in Figures 3A, one of the most common strategies of integrating solar cells on textile is through the functionalization of fibers and yarns, which can thereafter be weaved or sewn into the fabric (Chen et al., 2016;

Table 3. Selected examples of various textile-based energy harvesters fabricated via top-down and bottom-up strategies

Harvester type	Material/Type	Fabrication	Features	Max power	Ref
Solar	CuI, ZnO,Dye, Cu, PBT wire	Chemical plating/electroplating	Flexible	0.4 mW	(Chen et al., 2016)
	PCBM, Perroveskite, PEDOT: PSS, CNT	Printed/coated (top down)	Flexible	12.69 mA/cm^2 J_{sc} 0.82 V V_{oc}	(Jung et al., 2018)
BFC	GOx + BOD on SWCNT-PEDOT: PSS yarn	Bi-scrolled yarn (bottom up)	Flexible	1.5 mW/cm^2	(Kwon et al., 2014)
	LOx + Ag_2O on MWCNT	Printed, drop casting (top down)	Flexible, stretchable	250 uW/cm^2	(Chen et al., 2019; Lv et al., 2018)
PENG	Carbon black, PVDF, polyethylene fiber	Melt-spun (bottom up)	Flexible, washable	8 uW	(Lund et al., 2018)
	PZT, Ag nanoparticles	Printed, die pressed (top down)	Flexible	0.45 uW/cm^3	(Almusallam et al., 2017)
TENG	Cu/PTFE strips	Cut strips, woven (bottom up)	Flexible	0.8 mW	(Chen et al., 2016)
	Ni/Parylene	Electroless/chemical vapor deposition (top down)	Flexible, washable	4 mW	(Pu et al., 2016b)
TEG	SWCNT, PEI yarn	Colloidal gelation extrusion	Flexible, washable	0.1 uW	(Ding et al., 2020)
	PEDOT:SS, Na(NiETT), PVDF	Printed (top down)	Flexible, washable	0.5 nW	(Elmoughni et al., 2019)

Li et al., 2015). Typical solar cells generate power with density up to hundreds of $\mu W/cm^2$ from outdoor lighting, and their voltage and current can be adjusted upon changing its serial or parallel connections. Another fabrication strategy involves the direct deposition of the photovoltaic material onto textile substrates, which involves various thin and thick-film deposition techniques such as screen printing, dip coating, or spray coating (Figures 3B) (Arumugam et al., 2016). The as-fabricated solar cells are intimately integrated with the textile and flexible (Figures 3C) (Arbab et al. 2016).

TEs made of various organic and inorganic thermoelectric materials have been used for harvesting energy from the temperature gradient between human body and the surrounding environment. As the temperature gradient ranges from 5 to 20 K between the human body and the surrounding, a single cell can only generate an extremely low voltage. TEs using n-type and p-type thermoelectric materials can be connected in serial to increase voltage and power (usually in the order of $10–10^2$ mV, $10^{-1}–10^3$ pW). The power of TE varies with the load, with its ideal load equal to the internal resistance of the device. In addition to the serial connection, the direction of each p-n junction must be parallel with the temperature gradient, thus the design of the harvester requires skillful spatial arrangement. As shown in Figures 3D, the p-type material (PEDOT:PSS) and the n-type material (Poly[Na(NiETT)]) were arranged in a hexagonal layout and connected with a Hilbert curve to reach high fill factor of 30%, and the interconnections were printed to sequentially connect the n-type and p-type thermoelectric materials in series (Elmoughni et al., 2019). Alternatively, the thermoelectric material can be extruded into fibers with segments of p-type materials (CNT) and n-type materials (PEI-CNT), which were weaved into textile to establish a hierarchical structure of p-n junctions and generate >80 pW power per square of textile (Figures 3E) (Ding et al., 2020).

PENG and TENG bioenergy harvesters scavenge energy produced by the human movements and metabolism, and hence do not rely on the external environment and can generate power on-demand. Invented by Wang et al., in 2006 (Wang and Song, 2006), PENGs scavenge energy from mechanical deformation of piezoelectric materials that induce charge separation within the material (Figures 3F) (Wang and Song, 2006). A wearable PENG based on inorganic materials such as ZnO and lead zirconate titanate (PZT), or organic materials such as poly(vinylidene fluoride-co-trifluoroethylene) PVDF-TrFE is able to generate nW-μW power with several to tens of V alternating voltage from daily human movements (Khan et al., 2012; Lee et al., 2012; Mokhtari et al., 2020; Wu et al., 2012). As an example, shown in Figures 3G, the piezoelectric PVDF which is melt-spun into microfibers and weaved into textile generates power from its bending, twisting, and pulling (Lund et al., 2018). TENGs harvest energy from the relative motion between two materials that have different electron affinities (Fan et al., 2012). The energy harvesting using TENG has a variety of configurations to harvest energy from vertical contact-separation or from lateral sliding, harvesting the charge movement between either one electrode and ground or between two electrodes (Figures 3H) (Dong et al., 2019). As all materials have a certain affinity to electrons, the selection of materials

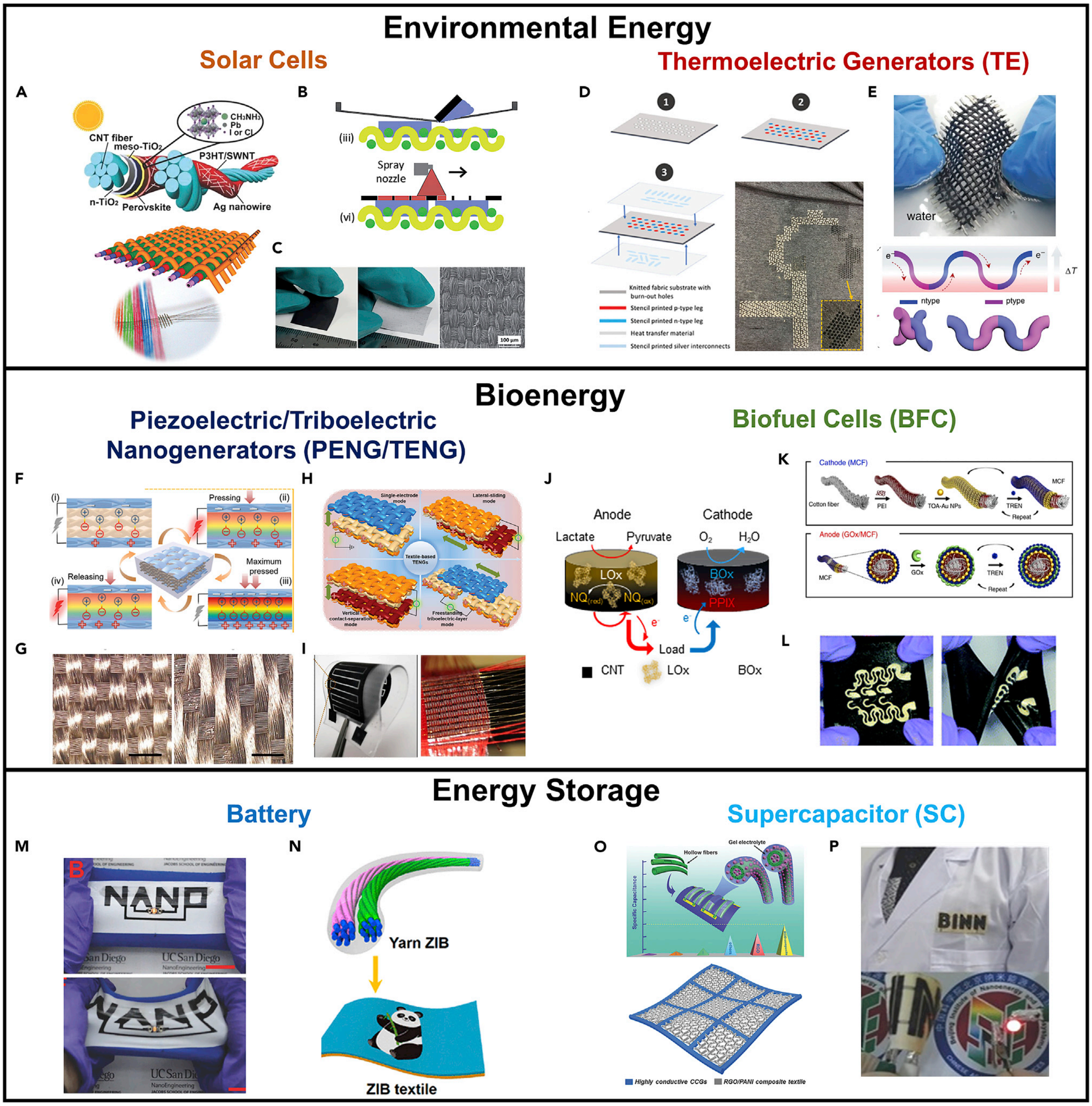

Figure 3. Constituents of wearable energy systems

(A) Yarn-based photovoltaic cells and its integration into a solar-based textile (Chen et al., 2016; Li et al., 2015).

(B) Printed, sprayed, and embedded solar cell using textile substrate (Arumugam et al., 2016). (C) Textile fabric-based hye sensitized solar cell (Arbab et al., 2016)

(D) Printed and hot-pressed thermoelectric devices on textile substrate (Elmoughni et al., 2019).

(E) Yarn-based thermoelectric device and the assembly of the yarns into textile (Ding et al., 2020).

(F) Charge generation methods of piezoelectric materials (Dong et al., 2019).

(G) Yarn-based triboelectric materials weaved into textiles (Lund et al., 2018).

(H) Four modes of charge generation in triboelectric nanogenerators (Dong et al., 2019).

(I) Printed piezoelectric generator (Paosangthong et al., 2019; Wen et al., 2019).

(J) Illustration of the charge-generation mechanism of biofuel cells (Yin et al., 2021a).

(K) Yarn-based glucose biofuel cells (Kwon et al., 2014).

Figure 3. *Continued*

(L) Printed textile-based lactate biofuel cells (Jeerapan et al., 2016).

(M) Printed textile-based silver oxide-zinc battery (Kumar et al., 2017).

(N) Yarn-based zinc ion battery and its integration in textiles (Li et al., 2018c).

(O) Yarn-based supercapacitor and their integration into textiles (Qu et al., 2016; Sun et al., 2016). (P) Printed textile-based flexible supercapacitor (Pu et al., 2016a).

is rather unlimited, with common negative electrode materials selected from electron-rich materials such as PTFE, PVC, PE, PP, and PS, and common positive electrode materials selected from positively charged materials such as aluminum, nylon, and cellulosic materials (Fan et al., 2012). The triboelectric materials can be deposited onto flexible substrates such as textiles or fabricated into yarn-type materials that directly weaves into textiles (Figures 3I), and thus harvest energy from body movements (Chen et al., 2016; Paosangthong et al., 2019; Wen et al., 2019). Similar to PENGs, the power generated from the TENGs are in alternating high voltage (tens to hundreds of volts) and requires regulation before the generated energy can be harvested and stored.

BFC, a promising wearable energy harvester, collects energy form metabolites in human biofluids, such as glucose, urea, alcohol, and lactate. As lactate has the highest concentration in sweat, BFCs based on lactate have been widely studied (Bandodkar and Wang, 2016; Chen et al., 2019; Jeerapan et al., 2020). The lactate-based BFCs rely on enzyme catalytic oxidation reaction to convert lactate into pyruvate on the bioanode, which is complemented by oxygen reduction reaction on the cathode catalyzed by Pt or BOx (Figures 3J) (Jeerapan et al., 2020; Jia et al., 2014; Yin et al., 2021a). As the BFC operates based on the availability of lactate in sweat, high-intensity exercise is usually required to generate significant amount of sweat. Different from PENG and TENG-based harvesters, the sweat can be stored in reservoirs or hydrogels for subsequent use, hence allowing energy harvesting even after movement stops. The BFC can be fabricated into yarn form factor, or printed onto textile substrates, and integrated onto shirts or garments to harvest energy from human perspiration (Figures 3K–3L) (Jeerapan et al., 2016; Kwon et al., 2014).

Textile-based energy storage devices

The energy storage device on wearable e-textile systems can be generally classified into two types: batteries and supercapacitors, both relying on the storage of charges in electrochemical cells. In general, the battery stores energy based on the redox conversion of the anode and cathode materials or the intercalation and deintercalation of cations that shuttles between the anode and cathode hosts. The supercapacitors store energy based on surface reactions on capacitive and pseudocapacitive electrodes, and rely on high surface area materials for non-faradaic double-layer charge adsorption (*e.g.* CNT, graphene, and Mxene) and desorption and highly reversible redox materials (*e.g.* conductive polymers, Prussian blue analogs, and TMD) (Borenstein et al., 2017; Hu et al., 2020a; Ke and Wang, 2016; Manjakkal et al., 2020). The batteries feature high capacity and energy density, with slower reaction rate, whereas the supercapacitors support higher power density due to its high reaction rate, high cycle life, yet has lower energy density compared to batteries.

Wearable Li-ion batteries have been developed with good flexibility and stretchability endowed by structural innovations (Xu et al., 2013; Yin et al., 2018a). However, they are prone to overheating and explosion and are deemed less suitable for wearable applications. In contrast, Zn-based batteries are much safer, easy to fabricate, and have variability in form factors (Li et al., 2018b, 2018c; Mo et al., 2020; Parker et al., 2017). Paring with oxygen in the air or the oxides of Mn, Ag, and Ni as cathode, a wide selection of batteries that are flexible, stretchable, and wearable has been developed in printable, planar configuration or in wire or yarn configuration, readily to be integrated with wearable electronics (Figures 3M–3N) (Kumar et al., 2017; Li et al.,2018b, 2018c). Printable Zn-based batteries have achieved areal capacity up to 54 mAh/cm^2 and current of up to tens of mA, demonstrating the ability to steadily power various kinds of microcontrollers and integrated systems with display and sensing functionalities (Yin et al., 2021c). High capacitance supercapacitors have also been developed that can supply instant high power to electronics and be rapidly recharged. Conductive polymer (e.g. PEDOT:PSS, PPy, and PANi) or 2D-material-coated yarns can be used to fabricate textile supercapacitors with hierarchical structures (Figures 3O) (Anasori et al., 2017; Qu et al., 2016; Sun et al., 2016; Xu et al., 2017). Similarly, such capacitive or pseudocapacitive materials can be formulated into printable inks to print on textile, which can be combined with special structures (e.g. serpentines) for structural stretchability or with elastomeric binders which endows intrinsic stretchability (Figure 3P) (Pu et al., 2016a).

Table 4. Selected examples of various textile-based energy harvesters fabricated via top-down and bottom-up strategies

Storage type	Material	Fabrication	Features	Capacity	Example
Li-ion battery	Graphite, $LiCoO_2$	Chemical plating/electroplating	Flexible, washable	25 mAh/m	(He et al., 2021)
	$Li_4Ti_5O_{12}$, $LiFePO_4$, denka black	Electroless deposition, Slurry coating	Flexible	13 mAh	(Lee et al., 2013)
Zn battery	MnO_2, CNT, Zn	Coated yarn (bottom-up)	Flexible, stretchable	1.5 mAh/cm	(Li et al., 2018c)
	Ag_2O, Zn, Super-P	Printed, drop casting (top down)	Flexible, stretchable	2.5 mAh/cm^2	(Kumar et al., 2017)
Supercapacitors	Reduced graphene oxide (rGO), Ni, Polyester	Melt-spun (bottom up)	Flexible	13 mF/cm	(Pu et al., 2015)
	COOH-CNT/MnO_2-CNT, PEDOT:PSS	Printed (top down)	Flexible, stretchable	~100 mF/cm^2	(Lv et al., 2018)

Table 4 Summarizes the key characteristics, structure, and fabrication of selected examples as discussed above

Integration of textile-based energy devices

With the development of various textile-based energy harvesters and storage devices, integrating different kinds of energy devices is a promising method to achieve unprecedented performance. Specifically, integrating different energy storage mechanisms enables both high power density and high energy density (Forouzandeh et al., 2020; Zuo et al., 2017). As examples, Figures 4A and 4B show several kinds of textile-based battery-supercapacitor hybrid devices based on VO_2 and Ni-Co selenide, respectively (Sahoo et al., 2019; Wang et al., 2020a). These devices allow rapid charge and discharge due to the use of highly redox-reversible pseudocapacitive transition metal oxides and dichalcogenides, and able to maintain relatively high energy density.

Likewise, the hybridization of energy harvester has also been widely explored (Chen et al., 2016; Lee et al., 2016; Li et al., 2020b; Ryu et al., 2019; Xu et al., 2021; Yin et al., 2021a). The integrations have been demonstrated on harvesters with similar working mechanisms, such as PENGs and TENGs (Song et al., 2018; Zhang et al., 2015b; Zhu et al., 2019), and harvesters with different working mechanisms, such as TENGs and photovoltaic materials (Chen et al., 2016; Pu et al., 2016b). As Figures 4C–4D show, a textile-based hybrid harvester integrates solar cells and TENGs to scavenge energy from two different sources, which enhances the system reliability when one of the energy sources is unavailable (Chen et al., 2016; Pu et al., 2016b).

To further enhance system reliability, energy storage devices are integrated with energy harvesters. Energy sources for wearable harvesters are highly irregular and uncontrollable, thus the storage units are required to store or output energy on-demand. Furthermore, the storage units are able to discharge at high current which the harvesters alone cannot supply, allowing utilization of high-power electronics on e-textiles. As shown in Figures 4E–4G, examples such as integrating solar cells, TENG, and BFC with supercapacitors on textile were explored, respectively (Chai et al., 2016; Lv et al., 2018; Pu et al., 2015; Wen et al., 2016). Such integration allows the energy harvested under sunlight or during movements to be stored for later use after the supply of sunlight, movements, or sweat stopped, hence extended the operation time of any electronics that may be powered by these harvesters.

Implementing these concepts, many self-powered, autonomous systems that incorporate energy harvesters, storage, power management circuits, data acquisition, and transmission electronics have recently been reported (Song et al., 2020; Yin et al., 2021a; Yu et al., 2020). Many works utilize a similar power utilization system, which stores the energy generated in capacitors or supercapacitors, and releases such stored energy in pulses to power microcontrollers or system-on-chips to perform the data acquisition-processing-transmission cycle within a few hundred milliseconds. System powered by BFC arrays or TENG has been reported to transmit sensing data of glucose, urea, temperature, or pH of sweat to cell phones without any external power supply (Song et al., 2020; Yu et al., 2020). Alternatively, e-textile system that

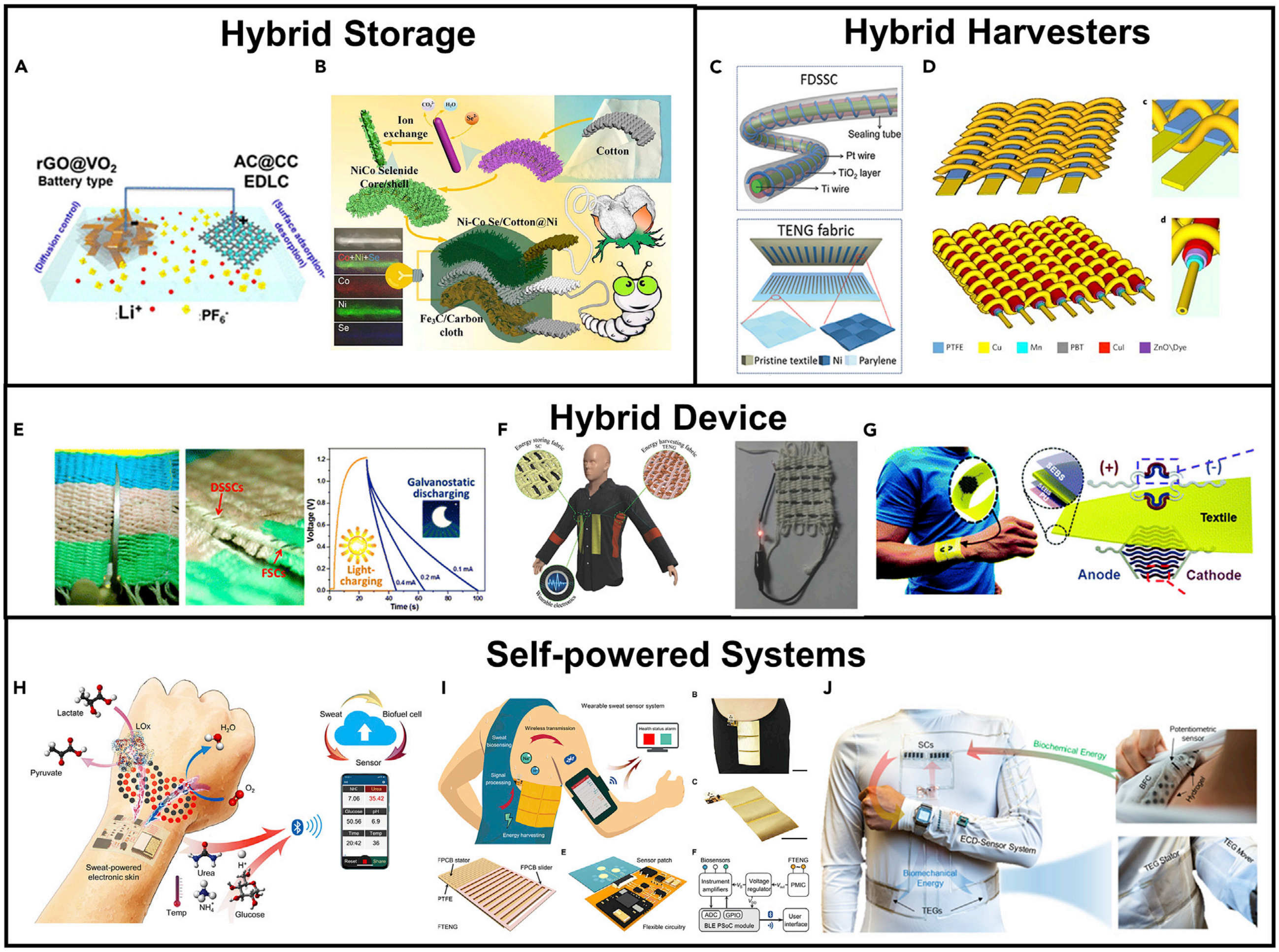

Figure 4. Different types of integration of energy devices on textiles

(A–J) (A and B) Textile-based hybrid battery-supercapacitor energy storage device (Sahoo et al., 2019; Wang et al., 2020a). Integrated hybrid harvester combining (C) wire-shaped solar cell and textile-based triboelectric generators, and (D) integration of triboelectric yarn and photovoltaic yarn into hybrid energy harvesting textile (Chen et al., 2016; Pu et al., 2016b). Hybrid harvesting-storage devices integrating (E) yarn-based supercapacitors and photovoltaic cells, (F) triboelectric nanogenerator textile and batteries, and (G) printed biofuel cells and supercapacitor on textiles (Chai et al., 2016; Lv et al., 2018; Pu et al., 2015). Examples of self-powered systems combining (H) biofuel cells, capacitor, electrochemical sensors and Bluetooth modules, (I) triboelectric nanogenerator, capacitor, and electrochemical sensors with wireless modules, and (J) textile-based all-printed system integrating biofuel cells and triboelectric generators as harvester, supercapacitor as storage device, and sensors with displays controlled microcontroller (Song et al., 2020; Yin et al., 2021a; Yu et al., 2020).

combines several harvesters and storage devices has been explored, aiming to establish a microgrid-on-shirt, and display the sensing result using electrochromic display directly, hence further removing the need for external mobile devices (Yin et al., 2021a; 2021b). Currently, as the energy scavenged from the harvesters is still limited in microwatt range, the functionality of the integrated systems is rather limited, compatible to only open-circuit potentiometric-based sensors. The integrated system also relies on inconvenient power input, such as exercises or direct sunlight, thus impeding the practicality of the device. Further improvement in the increasing power of on-body harvester while reducing the requirement for energy input is needed to truly expand the practicality and reliability of such self-powered systems.

WIRELESS COMMUNICATION FOR E-TEXTILE SYSTEM

Over the past decades, developments in materials and fabrication methods have yielded a wide range of sensors that can be implanted in the body (Stuart et al., 2021), attached on the skin (Tricoli et al., 2017), and integrated into textiles (Hatamie et al., 2020) to acquire physiological signals. Textiles, as the second human skin, provide a unique platform for integrating wireless functionality (Heo et al., 2018; Shi et al.,

Table 5. Typical textile-integrated modules for wireless communication

E-textile for wireless communication	Material	Fabrication	Features	Ref
Textile attached modules	Metal on polymer substrate	Printing, etching	Flexible	(Mishra et al., 2018; Niu et al., 2019)
Textile antennas	Metal nanomaterial	Printing, coating	Flexible	(Jin et al., 2017)
	Conductive thread	Embroidery	Flexible, washable, permeable	(Lin et al., 2020)
Body networks	Conductive fabric	Laser cutting	Flexible, washable	(Tian et al., 2019)

2020; Weng et al., 2020; Zeng et al., 2014), and eventually establishing a digital communication network that wirelessly interconnects these sensors with the digital world (Xie et al., 2020). Unlike direct wiring method that is widely used in clinical and research settings, such a wireless communication network enables continuous health monitoring without temporal and spatial restraint (Cao et al., 2009; Cui et al., 2019; Liang and Yuan, 2016). In this section, we will introduce the mechanism of wireless communication, integration of wireless module with textiles, textile antennas, and textile-based body sensor networks. We briefly summarize typical materials, fabrication methods, and features of textile-integrated wireless modules in Table 5.

Wireless communication transfers information between two or multiple devices through electromagnetic field ("RFID Handbook," 2010). Near-field communication (NFC) and Bluetooth are the most widely used approaches. In these wireless technologies, the reader antenna generates a time-varying magnetic field, which develops a time-varying electric field by electromagnetic induction, and mutual dependence of these time-varying fields generates a chain effect of electric and magnetic fields in space. In the near-field, at where the distance between the reader and the transponder is within the wavelength of electromagnetic field, wireless interconnection is achieved through inductive coupling (Figure 5A). In the far field, such interconnection is established through backscatter coupling at where a small proportion of emitted electromagnetic field reflected by the responder is received by the reader antenna (Figure 5B). The transponder microprocessor converts the data stream to switch on and off the load resistor connected with the antenna, which affects the inductive coupling or backscatter coupling and eventually transmit the data to the reader ("RFID Handbook," 2010).

Advancement on CMOS technology has enabled minimization of electronics and incorporation of wireless modules into tiny chips with millimeter dimensions. Integrating embedded chips and passive components directly on textile remains a challenge and requires innovation on electronic materials and fabrication methods. Alternatively, a flexible printed circuit board (PCB) is used to assemble all electronics and then physically attached or adhered on textile (Mishra et al., 2018; Niu et al., 2019). The wireless module can be further connected with sensors wirelessly or wired. In the wireless approach, the sensor is part of the passive LC circuit and converts the sensing signal to resonant frequency shift or magnitude variation (Figure 5C) (Nie et al., 2019; Niu et al., 2019). As there is no physical connection, the sensor can not only be on textile (Nie et al., 2019) but also on skin and even implanted in deep tissue (Boutry et al., 2019; Niu et al., 2019; Yeon et al., 2019). The LC circuit can be free of fragile silicon-integrated circuits and completely soft, offering a conformal skin-mimicking interface. However, the inductive coupling between the wireless module and sensor may be affected by surrounding environment such as moisture, human touch, and relative motion, and thus eventually affect data accuracy (Huang et al., 2016; "RFID Handbook," 2010). The wired method is generally used to connect the wireless module with textile-integrated sensors (Figure 5D) (Kassal et al., 2018; Mishra et al., 2018). These textile-integrated systems are wearable version of bench-top devices and able to employ most conventional methods such as electrochemical, electrical, and optical measurement to detect various kinds of physiological and biochemical signals (Kassal et al., 2018).

Even though minimization makes wearable electronics to be less obtrusive for users, miniaturizing antennas, the critical component for wireless communication, generally deteriorates antenna performance. Instead, textile antenna, which is composed of a textile conductive element and another textile material acting as substrate, is a promising candidate for constructing unobtrusive wearable communication network (Ali et al., 2020; Alonso-Gonzalez et al., 2019; Kennedy et al., 2009; Roh et al., 2010). Utilizing textile

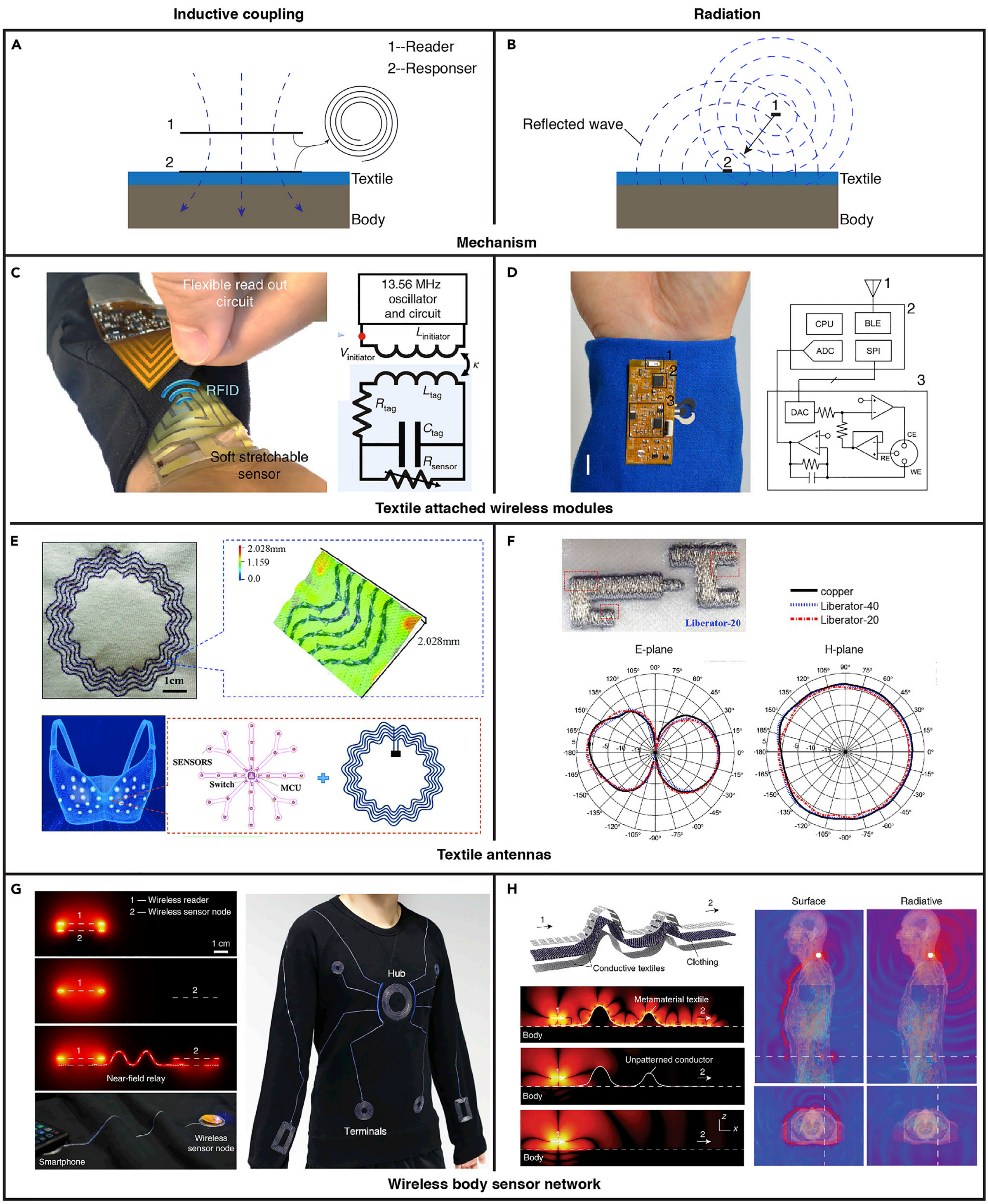
Inductive coupling
Radiation
A
1--Reader
2--Responser
1
2
Textile
Body
B
Reflected wave
1
2
Textile
Body
Mechanism
C
Flexible read out circuit
RFID
Soft stretchable sensor
13.56 MHz oscillator and circuit
D
1
2
3
CPU
BLE
ADC
SPI
DAC
CE
RE
WE
Textile attached wireless modules
E
2.028mm
1.159
0.0
2.028mm
1cm
SENSORS
Switch
MCU
F
Liberator-20
copper
Liberator-40
Liberator-20
E-plane
H-plane
Textile antennas
G
1 — Wireless reader
2 — Wireless sensor node
1 cm
Near-field relay
Smartphone
Wireless sensor node
Hub
Terminals
H
Conductive textiles
Clothing
Metamaterial textile
Body
Unpatterned conductor
Body
Body
Surface
Radiative
Wireless body sensor network

Figure 5. E-textile for wireless communication

(A–H) Illustration of wireless communication by (A) inductive coupling and (B) radiative technique. Textiles are platforms for (C and D) directly attaching wireless communication modules (Mishra et al., 2018; Niu et al., 2019), (E and F) seamlessly integrating antennas (Kiourti and Volakis, 2015; Xu et al., 2019), and (G and H) building wireless body sensor network (Lin et al., 2020; Tian et al., 2019). (C and H) Copyright 2019, Nature Publishing Group. (D) Copyright 2018, Elsevier. (E) Copyright 2019, Wiley-VCH. (F) Copyright 2015, IEEE. (G) Copyright 2020, Nature Publishing Group.

material enables antennas to be thin, lightweight, flexible, robust, inexpensive, and easily integrated into a garment, thus making the textile antennas comfortable for wear and durable for long-term usage (Figure 5E) (Ali et al., 2020; Xu et al., 2019). Antenna performances such as radiation pattern, gain, resonant frequency, and bandwidth are significantly affected by material characteristics (Brebels et al., 2004; Koski et al., 2014; Salvado et al., 2012). For instance, antenna bandwidth and efficiency are significantly affected by permittivity and thickness of the dielectric substrate. In general, textiles present a very low dielectric constant with relative permittivity close to one as they are very porous materials. As the porous structure can be easily deformed by bending and stretching, and can facilitate air exchange with moisture under the effect of environmental temperature and humidity, the textile's permittivity may change dynamically and result in unstable antenna performance. The textile conductive threads generally have much lower electrical conductivity compared with metal tracks, resulting in high power loss and low antenna efficiency (Salvado et al., 2012). Innovation in material, fabrication process, and antenna design could enable textile antenna performance similar to that of conventional metal antenna and even maintain performance under various circumstances such as mechanical deformation and harsh environmental factors (Figure 5F) (Kiourti and Volakis, 2015; Lilja et al., 2012; Wang et al., 2012, 2014).

Wireless body sensor network which simultaneously record signal from multiple anatomical locations can enhance the utility and reliability of the sensors in broad applications ranging from vital signs monitoring to fitness tracking (Yang, 2014). Conventional wireless body sensor networks rely on radio-based technologies, such as Bluetooth, and require each sensor node to be separately powered, typically using rigid batteries or bulky energy harvesters. These components limit the degree of skin conformability and user comfort that can be achieved and require periodic replacement or availability of specialized energy sources for long-term function. In addition, the radiative nature of data transmission results in vulnerabilities to eavesdropping and necessitates the use of cryptography techniques to address privacy concern (Yang, 2014). To overcome these shortcomings, textile-based wireless body sensor network has been developed.

Near-field-enabled clothing relies on inductive coupling to establish wireless power and data connectivity around the human body (Figure 5G) (Lin et al., 2020). Specifically, the near-field-enabled clothing is fabricated by using computer-controlled embroidery to integrate low-cost conductive threads in textiles with near-field-responsive inductor patterns. By placing devices near to these patterns, the time-varying magnetic field generated by the reader such as smartphone can be transferred to other connected patterns with meter-scale distance from the hub (proximity to the reader) and then to the respective sensor nodes. Metamaterial textiles which are clothing structured with conductive textiles can support surface-plasmon-like modes at communication frequencies and thus provide a platform for the propagation of radio waves around the body (Figure 5H) (Tian et al., 2019). When standard wireless devices are placed near metamaterial textiles, their interconnection can be achieved through the propagation of wireless signals as surface waves instead of wireless signals radiating into the surrounding space. Both the near-field-enabled clothing and metamaterial textiles transfer the wireless signal across conductive textile other than over air, enabling the network to operate with high efficiency. The physical localization of wireless signals on body surface ensures the networks immune to interference and inherently secure. In contrast with prior efforts to integrate wireless modules into textiles, the near-field-enabled clothing and metamaterial textiles do not incorporate fragile silicon-integrated circuits or require physical connectors with nearby devices, they are entirely fabric-based and are robust to daily wear.

CONDUCTORS FOR E-TEXTILES

Electrical conductor that can be integrated on textiles, term textile conductor, is a critical component to interconnect discretely distributed modules around human body and form an independent e-textile system (Mulatier et al., 2018; Wang and Facchetti, 2019). Textile conductors should not only have high electrical conductivity as metal conductors to form a power bus and data network but also maintain conventional textile properties to enable durable and comfortable wearing, thus require innovation on both material and fabrication methods.

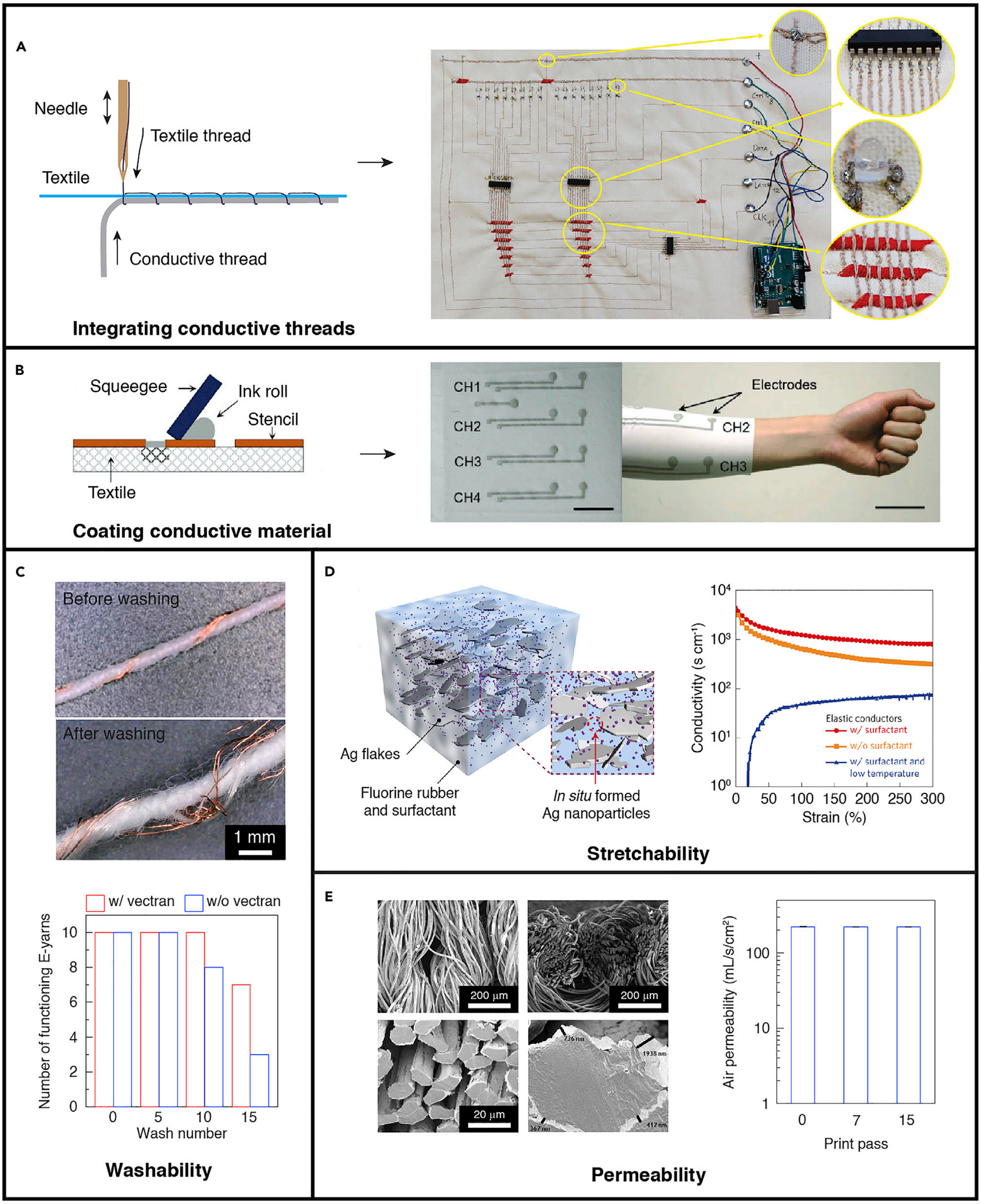
A
Needle
Textile thread
Textile
Conductive thread
Integrating conductive threads
B
Squeegee
Ink roll
Stencil
Textile
Coating conductive material
CH1
CH2
CH3
CH4
Electrodes
CH2
CH3
C
Before washing
After washing
1 mm
w/ vectran
w/o vectran
Number of functioning E-yarns
Wash number
Washability
D
Ag flakes
Fluorine rubber and surfactant
In situ formed Ag nanoparticles
Conductivity (s cm⁻¹)
Strain (%)
Elastic conductors
w/ surfactant
w/o surfactant
w/ surfactant and low temperature
Stretchability
E
200 µm
200 µm
20 µm
Air permeability (mL/s/cm²)
Print pass
Permeability

Figure 6. Conductors for e-textiles

(A–E) Textile conductors are fabricated by (A) integrating conductive threads (Ismar et al., 2020), and (B) coating conductive material (Jin et al., 2017). Key performances of the textile conductive materials include robustness against (C) washing (Hardy et al., 2020) and (D) mechanical deformation (Matsuhisa et al., 2017) and (E) water/air permeability(I. Kim et al., 2019a).(A) Copyright 2020, IEEE. (B) Copyright 2017, Wiley-VCH. (C) Copyright 2020, MDPI. (D) Copyright 2017, Nature Publishing Group. (E) Copyright 2019, Wiley-VCH.

Several methods have been developed to fabricate textile conductors and can be classified into two categories. One is to integrate conductive threads on textile by using conventional textile methods such as knitting, weaving, sewing, and embroidering (Figure 6A) (Ismar et al., 2020; Mohamadzade et al., 2019; Roh, 2017, 2018; Sanchez et al., 2021; Tsolis et al., 2014). The conductive threads include commercially available yarn such as metal-plated, metal filament, and stainless-steel yarns, and polymer threads functionalized with nanomaterial such as nanowires, nanoparticles, and carbon material. While these integration processes are completely solvent-free and compatible with the conventional textile fabrication equipment and largely maintain textile properties, they generally only achieve millimeter-scale pattern resolution, and the threads are subjected to serious mechanical deformation during fabrication.

The other method is to functionalize textiles with conductive material through printing, coating, or deposition (Figure 6B) (Andrew et al., 2018; Jin et al., 2017; Mohamadzade et al., 2019; Wang and Facchetti, 2019). As textiles are 3D porous structures consisting of a network of interconnected fibers or yarns, these methods create conductive paths on the textiles by filling the voids or the network with conductive ink, paste, or precursor, followed by thermal curing or reaction to form metal composite/coating. While the metal conductive paths can achieve high electrical conductivity, they generally stiffen the textile, block moisture, and are vulnerable to crack or delamination under mechanical deformation.

To implement textile conductors on durable and comfortable wearing, innovation of material and fabrication methods should enable textile conductors with several distinct properties. The textile conductors should maintain high electrical conductivity under repeatable mechanical deformation as they are subjected to stretching, bending, and washing frequently. Pure metallic conductors such as metallic filament yarns generally have low yield point, and thus susceptible to breakage under bending/washing (Figure 6C) (Hardy et al., 2020). Metallic composites consist of conductive fillers added into a polymer matrix to increase the yield strain, which confers the conductor's stretchability at the cost of decreased electrical conductivity (Figure 6D) (Jin et al., 2017; Lee et al., 2015; Matsuhisa et al., 2015, 2017). Achieving high electrical conductivity with robustness remains a key challenge for textile conductors. To maintain wearable comfortability of textile, the textile conductor should also be lightweight, breathable, and flexible. As such, the textile should maintain its 3D porous structure after functionalized with conductive materials (Figure 6E) (Kim et al., 2019a; Wu et al., 2018). Finally, the textile conductors should have an insulating layer to protect the wearer and prevent the circuit from effects of temperature, sweat, moisture, and accidental splash (Yin et al., 2018b).

CONCLUSIONS

Owing to their considerable potential for wide application in various fields, e-textile systems have attracted much attention from researchers. These applications include physical, chemical, and biological sensing, energy harvesting, storage, and data interfacing with other smart devices. Studies conducted on e-textiles include washability, nontoxicity, biocompatibility, and mechanical performance, all of which are crucial toward practical applications. Nevertheless, limitations still exist in e-textile systems that impede their development as commercial consumer products.

Limitations of e-textile sensors

Firstly, the quality and repeatability of e-textile sensors are difficult to control. Compared with ordinary electronics, the dimension of electronics in e-textiles are comparatively smaller, so that flexibility and wearability can be achieved. However, the small size of these fibers or thin layers of coating may make the high quality and repeatability difficult to achieve. Most of the reported smart e-textiles are produced in lab and only at the "proof of concept" stage, without taking quality and repeatability of the sensor into consideration.

Secondly, there is lack of mass production capability. Most of the smart e-textiles are produced in lab by hand. On the other hand, most of these e-textiles are produced either using expensive materials or with complicated fabrication method, which may lead to high production cost and less acceptable by the market. Thus, mass production capability is difficult to achieve for most of the laboratory produced e-textiles.

Thirdly, there is lack of standardization. Even for the same application, different e-textile sensors may have different testing range, resolution, cycle life, hysteresis, and other aspects owing to different materials used, fabrication methods, and working mechanism behind different e-textiles. As such, it is difficult to evaluate or compare the different e-textiles. In order to make e-textile commercially available in the future, standard evaluation system is necessary at least for e-textile with mainstream production methods.

Furthermore, the functionality of some e-textile sensors, especially for bio/chemical sensors, relies highly on reactants that have been integrated in the textile. This may lead to the issue that once the reactants have depleted to a certain level, these e-textile sensors will lose the sensing capability before the reactants are being replenished.

In addition, lacking of compatible technologies may also hinder the development of e-textile sensors. Most of the reported e-textiles are mainly focused on one single component, sensor, energy harvester, or connection. However, every single component cannot work by itself but requires other compatible technologies to support it. For example, some of the e-textiles sensors may require high power energy device, which may not be currently available in the e-textile market. In order to use these e-textile sensors, a bulky battery may need to be connected to the sensor, thus affecting the flexibility and wearability of e-textiles.

Limitations of e-textile energy harvesters and storage systems

Energy harvesting still remains the most significant bottleneck for the energy self-sufficiency of the wearable electronics ecosystem, as the energy generated for practical use is only able to power electronics in very limited applications. We envision future developments in novel materials (e.g. 2D materials, conductive polymers, and high-entropy alloys), fabrication methods, and device structures in existing e-textile energy harvesters to bring improvements in performance, wash-durability, and stretchability. Furthermore, as more energy harvesting mechanisms are explored, energy harvesting system that works in more diverse environment and scenarios may be made available to diversify the energy input to e-textile systems.

Current energy storage is limited by their energy density, power density, and cycle life (Yin et al., 2021c). Hence, the functionality of e-textile systems is limited not only by their performance but also their need for frequent recharge. Although some attention has been directed to incorporate energy harvesters in wearable systems, their power is generally limited, and no harvesters are yet commercially available for use in e-textiles. Nevertheless, the concept of wearable microgrid has been proposed recently, advocating the critical budgeting of energy and power in e-textile systems to enhance the practicality and reliability of wearable energy systems, and its development will rely on multidisciplinary collaboration to make it a success (Yin et al., 2021a; 2021b).

Limitations of e-textile communication systems

Textiles have been demonstrated as a unique platform for integrating wireless functionalities and bridging the human body with surrounding physical world without temporal and spatial constraints. To enable public acceptance of wireless e-textiles as conventional clothing, several key challenges still remain and need to be overcome.

Firstly, material and manufacturing innovations are required to seamlessly integrate wireless functionalities into conventional textiles to achieve both high performance on wireless communication and durability/comfortability for wearing. For example, textile conductive materials are the basic elements for textile antennas. However, current textile conductive materials are either limited to low electrical conductivity, which seriously affected the wireless powering transfer efficiency, or low mechanical robustness, which causes e-textiles to lose their functionalities during daily wearing or washing.

Secondly, novel wireless technologies are required to build a secure wireless network between multiple devices distributed on textiles, skin, and even inside the body. Such a network would enable continuous monitoring of physiological signals that are once invisible and achieve clinical quality data outside the hospital. Power and data must be transmitted reliably across those devices during daily activities without temporal and spatial constraints. The network should also be highly secured against eavesdropping to maintain personal data privacy.

To sum up, e-textile is a unique platform that can provide tremendous value to applications such as personalized healthcare, robotics, virtual/augmented reality, and human-machine interface. There are tremendous opportunities in building innovative e-textile products that can revolutionize our lifestyles and eventually the way people conceptualize clothing and textiles. As such, the potential is there for e-textile to become a disruptive technology. However, to develop a complete e-textile product, researchers need to focus not only on the development of individual components but also on the seamless integration of these different components into a complete system with compatible form factors that confer comfort and wearability. We just need to continually engage industrial collaborators and investors to eventually transform lab-ready prototypes into commercially viable products.

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AUTHOR CONTRIBUTIONS

Conceptualization, K.D., R.Z.L., and Y.L.; Investigation, K.D., R.Z.L., and Y.L.; Writing–Original Draft, K.D., R.Z.L., and Y.L.; Writing–Review & Editing, K.D., R.Z.L., Y.L., J.S.H., J.W., and C.T.L.; Supervision, J.S.H., J.W., and C.T.L.; Funding Acquisition, C.T.L.

DECLARATION OF INTERESTS

The authors declare no conflict of interest.

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